Advancing Underwater Acoustic Communication for Autonomous Distributed Networks via Sparse Channel Sensing, Coding, and Navigation Support

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LONG-TERM GOALS

The long-term goal is to significantly advance underwater acoustic communication technologies for autonomous distributed underwater networks, through innovative signal processing, coding, and navigation algorithms. Providing highly reliable and high data rate communication links will be critical towards the development of a new era of underwater distributed networks.

OBJECTIVES

We have three objectives in this project.

1. **Advanced communication techniques of sparse channel sensing and nonbinary LDPC coding.** Underwater acoustic channels are naturally sparse, but how to effectively exploit the sparsity is a challenging task. We will investigate the recently developed "compressive sensing" algorithms for sparse channel estimation in the context of multicarrier acoustic communications. On the other hand, channel coding is one integral part of an advanced communication system, and is dispensable in approaching the theoretical limit predicted by the Shannon theory. We will thoroughly investigate nonbinary low-density-parity-check (LDPC) codes, and especially pursue fast encoding and decoding algorithms and practical implementations.
2. **High-resolution ranging and navigation.** Wideband multicarrier waveform has a dual use that it can yield precise timing information for the receiver to infer the distance from the sender. With range estimates from multiple buoys, each underwater vehicle can self localize and navigate. We will investigate ranging and tracking algorithms that achieve high positioning accuracy. We aim to integrate the communication and navigation capabilities into the OFDM modem under development, which will greatly facilitate the development of emerging underwater distributed networks.

3. **Testbed development and medium access control.** We plan to develop a network testbed to illustrate the cooperative networking scenario. We first will determine an effective medium

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access control protocol to improve the system throughput for multiple users equipped with high-rate OFDM modems. We will then carry out demonstrations in three settings: 1) point to point links with advanced communication techniques; 2) ranging and navigation in a setup with four buoys and one underwater node; and 3) cooperative networking in a setup with four buoys and multiple underwater nodes.

APPROACH

Our technical approach is to develop advanced signal processing algorithms to improve the robustness and increase the data rate of underwater acoustic communication. Specifically, 1) we will use compressive sensing algorithms to exploit the sparsity nature of the underwater acoustic channels, 2) we will develop advanced capacity-achieving nonbinary LDPC codes to improve the error performance, 3) we will improve the localization and navigation performance through the use of wideband OFDM waveforms, which has much increased time-resolution for ranging purposes, and 4) we will investigate effective medium access protocols along with a testbed demonstration with multiple nodes.

We work with Dr. Jie Huang from the University of Connecticut (UConn) to carry out the research tasks on sparse channel estimation and nonbinary LDPC coding. We collaborate with Drs. Zhijie Shi and Jun-Hong Cui from UConn on testbed development.

WORK COMPLETED

In this year, we have developed several advanced receiver algorithms, with real data sets collected in the following two major experiments.

1) SPACE08 experiment, Martha's Vineyard, MA, Oct. 2008 (led by Dr. James Preisig)
2) MACE10 experiment, Martha's Vineyard, MA, July 23, 2010. (led by Mr. Lee Freitag).

We continue to interact with Dr. Josko Catipovic to develop receiver algorithms for OFDM in deep water channels with very large delay spread and external interference. The experimental data were collected in the Atlantic Undersea Test and Evaluation Center (AUTEC) around Andros Island near the Tongue of the Ocean, Bahamas, Dec. 2008 and March 2010.

We have been using the OFDM modem prototypes to test the localization algorithm in a swimming pool and in local lakes. Furthermore, we have started to integrate advanced networking protocols to the OFDM modem prototypes. Initial tests have been conducted in the water tank.

We have supervised three undergraduate students into research through their senior design project:

- Project: "Power Amplification and Multiple Access Protocols for Underwater Acoustic OFDM Communication". Duration: Fall 2010- Spring 2011. Team: Timothy Jacobson, Ryan Menner, and Steven Milligan.

RESULTS

We next highlight our progresses made on the following topics: 1) Clustered adaptation for estimation of time-varying underwater acoustic channels. 2) Progressive intercarrier and co-channel interference mitigation for underwater acoustic MIMO-OFDM. 3) Turbo equalization for OFDM modulated physical layer network coding. 4) Blind CFO estimation for zero-padded OFDM over underwater acoustic channels 5) Structured nonbinary rate-compatible low-density parity-check codes. 6) Localization and tracking of underwater physical systems. 7) NAMS: A networked acoustic modem system for underwater applications. 8) OFDM receiver design in the presence of external interference.

1) Clustered Adaptation for Estimation of Time-Varying Underwater Acoustic Channels. We have developed a sparse channel estimator that exploits channel coherence across blocks for orthogonal frequency division multiplexing (OFDM) in underwater acoustic (UWA) transmissions. We have proposed a novel channel variation model that the channel paths within a cluster share the same amplitude, delay, and Doppler scale variations from one block to the next, but different clusters vary independently. The variation offsets for different clusters are estimated based on the measurements on the pilot subcarriers of the current block. A hybrid channel estimator is developed that can effectively utilize both the channel knowledge from the previous block and the pilot observations of the current block. Figure 1 shows the flow chart of the processing for the nth block in the proposed block-to-block receiver design. Figure 2 shows a sample of a channel estimate, where the channel paths fall within different zones.

Performance results based on collected data from two experiments demonstrate that adaptation with multiple clusters outperforms that with one cluster, and that the proposed cluster-adaptation based channel estimator significantly improves the system performance relative to the pilot-based counterpart; See Figure 3 for a performance illustration.

2) Progressive Intercarrier and Co-channel Interference Mitigation for Underwater Acoustic MIMO-OFDM. MIMO-OFDM has been actively studied for high data rate communications over the bandwidthlimited underwater acoustic (UWA) channels. Unlike existing receivers that treat the intercarrier interference (ICI) as additive noise, we have dealed with ICI explicitly together with the cochannel interference (CCI) due to parallel transmissions in MIMO-OFDM.

Our proposed receiver has the following components: 1) compressed-sensing (CS) based sparse channel estimation, 2) soft-inputsoft- output MMSE/Markov Chain Monte Carlo (MCMC) detector for interference mitigation, and 3) soft nonbinary LDPC decoding. These components are integrated under a progressive receiver framework, as shown in Figure 4, where the receiver starts with low-compleixty ICI-ignorant processing, and then progresses to ICI-aware processing with increasing ICI levels. In addition to simulation, we use real data from the SPACE08 and MACE10 experiments to verify the system performance, where the transmitter in SPACE08 was stationary and that in MACE10 was slowly moving. Simulation and experimental results show that explicitly addressing ICI and CCI significantly improves the performance of MIMO-OFDM in underwater acoustic systems; an example performance plot is shown in Figure 5 with four transmitters on a moving platform.

3) Turbo Equalization for OFDM Modulated Physical Layer Network Coding. We have investigated a practical orthogonal frequency division multiplexing (OFDM) modulated and low-density parity-check (LDPC) channel coded two-way relay system employing physical-layer network coding (PLNC),

where two terminals A and B desire to exchange information with each other with the help of a relay R which can be equipped with multiple receive antennas, as shown in Figure 6.

The critical process in such a system is the calculation of the network-coded transmit codeword at the relay on basis of the superimposed channel-coded signals of the two terminals. Different from existing works on non-iterative receiver design, we here consider iterative receiver design. We have proposed two turbo equalization receivers, one is the conventional iterative separate detection and decoding (I-SDD), and the other one is based on a recently developed estimation scheme for PLNC. Gaussian message passing (GMP) and sum-product algorithm (SPA) are used for ICI-aware equalization and channel decoding respectively. We find through numerical simulations that the performance of the I-SDD receiver can catch up with that of the state-of-the-art PLNC-based receiver when more than one receive antennas are used. One promising feature about the ISDD receiver is that the channel decoding complexity is much lower than that of the PLNC-based receiver.

4) Blind CFO Estimation for Zero-Padded OFDM over Underwater Acoustic Channels. We have compareed the performance and complexity of three existing blind carrier-frequency-offset (CFO) estimators when they are applied to estimate the residual Doppler shift for zero-padded OFDM transmissions over underwater acoustic channels: the null subcarrier based method, the O-M algorithm, and the Y-G algorithm. Performances of these three methods are evaluated by extensive numerical simulations and by data sets collected from the MACE10 experiment. Simulation results show that the Y-G algorithm always outperforms the O-M algorithm. As far as the fractional part of CFO is concerned, the Y-G algorithm can perform as good as the null subcarrier based method yet with a much lower computational complexity.

When working with real data, the Y-G algorithm needs to be modified and integer CFO estimation based on a few null subcarriers is incorporated. With considerations on the performance-complexity tradeoff and the overhead spent on null subcarriers, we make the following recommendations. 1) When the implementation complexity is not a concern for real time decoding and there are enough null subcarriers, the null subcarrier based method is preferred, having robust performance for all constellations. 2) When the implementation complexity needs to be kept minimum, or, when there are no or only a few null subcarriers embedded in the transmissions, the modified Y-G algorithm is a good choice for small to moderatesize constellations. The modified Y-G needs to be coupled with an integer CFO estimator, which is usually easy to construct and is not necessarily based on null subcarriers.

5) Structured Nonbinary Rate-Compatible Low-Density Parity-Check Codes. While existing works on rate-compatible low-density parity-check (RC-LDPC) codes, either binary or nonbinary, all focus on random-like construction, we in this letter present a novel method to construct structured nonbinary RC-LDPC codes. Protograph-based design with structured puncturing is applied while numerical simulation of code performance is adopted for optimization. The resultant codes are qualified as nonbinary quasi-cyclic LDPC (QC-LDPC) codes which are amenable to high-speed implementation of encoder/decoder. The code structure is shown in Figure 7. Numerical results in Figure 8 show that the proposed codes achieve very good performance. These are very practical codes that can be used for underwater acosutic relay networks.

*6) Localization and Tracking of Underwater Physical Systems.*We have investigates the problem of localizing an underwater sensor node based on message broadcasting from multiple surface nodes. With the time-of-arrival measurements from a DSP-based multicarrier modem, each sensor node localizes itself based on the travel time differences among multiple senders to the receiver. Using one-

way message passing, such a solution can scale to accommodate a large number of nodes in a network. Continuing on our preliminary work reported last year, we have focused on the tracking solutions at the node processing layer. We have carried out tests in a swimming pool with both stationary and moving receivers.

For the moving test in the pool, a simple straight-line maneuver was carried out, as shown in Figure 9. The interacting multi-model (IMM) filter with coordinated trun offers considerable reduction in the overall position error relative to single Kalman filter, as shown in Figure 10.

7) NAMS: A Networked Acoustic Modem System for Underwater Applications. We have developed a networked acoustic modem system (NAMS) by integrating a high-speed OFDM modem and a comprehensive underwater network protocol stack for underwater applications. This integrated system allows different underwater network protocols to run on top of the OFDM modem platform and can provide high-speed, reliable and efficient communications in underwater environments.

With NAMS, we conducted experiments in our laboratory. We tested a medium access control (MAC) protocol, UWAloha, in order to study the performance of NAMS for underwater networks. The experiments were done in an aquarium filled with water. The size of the aquarium is 2m x 1m x 1m. It could represent an environment with strong multipath effects which are typically found in shallow water area. As shown in Figure 11, we used four OFDM modems and conducted experiments in a single hop network settings.

In this scenario, three network nodes were trying to send messages to a single data sink. Figure 11 shows the performance of NAMS in the single hop scenario. The x-axis denotes the combined network traffic load, which is the sum of all network nodes. The y-axis denotes the throughput perceived by users at the application layer. In other words, this is the effective network data rate excluding all protocol overhead. As shown in Figure 11, within a single hop network, despite the intensive channel contentions from several data sources, NAMS can achieve an effective application layer throughput of around 636 bps.

8) Parameterized Cancellation of Partial-Band Partial-Block-Duration Interference for Underwater Acoustic OFDM. Despite that underwater acoustic channels are well known to contain various interferences, research on interference mitigation in underwater acoustic communications has been very limited. Recently, we have dealted with a wideband orthogonal frequency division multiplexing (OFDM) transmission in the presence of an external interference which occupies partially the signal band and whose time duration is shorter than the OFDM block. We parameterize the unknown interference waveform by a number of parameters assuming prior knowledge of the frequency band and time duration of the interference, and develop an iterative receiver, which couples interference detection via a generalized likelihoodratio-test (GLRT), interference reconstruction and cancellation, channel estimation, and data detection.

This work was primarily motivated by our observations in an experiment held in March, 2010, over one underwater network deployed at the Atlantic Undersea Test and Evaluation Center (AUTEC) around Andros Island near the Tongue of the Ocean, Bahamas. During the transmission of communication signals, other unknown users were transmitting multiple sonar waveforms in the same environment. The received communication signal at certain sensors was thus superimposed with the sonar transmissions as shown in Figure 13. In Figure 14, we show that the proposed receiver with

interference cancellation outperforms that without interference cancellation considerably, and the performance improvement brought by the iterative interference cancellation is significant.

IMPACT/APPLICATIONS

The success of our project will have a deep impact. Providing high-data-rate and reliable acoustic communication with navigation functionalities, our project will directly contribute to the development of distributed autonomous underwater networks that are of great interest to Navy, e.g., the AUV/UUV/Glider networks.

PUBLICATIONS

1. Z.-H. Wang, S. Zhou, J. Catipovic, and P. Willett, ``Parameterized Cancellation of Partial-Band Partial-Block-Duration Interference for Underwater Acoustic OFDM", IEEE Transactions on Signal Processing, 2011 [submitted].

2. H. Yan, L. Wan, S. Zhou; Z. Shi, J.-H. Cui, J. Huang, H. Zhou, ``DSP based Receiver Implementation for OFDM Acoustic Modems," Elsevier Journal on Physical Communication, 2011, doi:10.1016/j.phycom.2011.09.001. [published].

3. W. Tang, J. Huang, L. Wang, and S. Zhou, ``A Nonbinary LDPC Decoder Architecture with Adaptive Message Control," IEEE Transactions on Very Large Scale Integration Systems, 2011. [in press].

4. J. Huang, W. Zhou, and S. Zhou, ``Structured Nonbinary Rate-Compatible Low-Density Parity-Check Codes," IEEE Communications Letters, vol. 15, no. 9, pp. 998-1000, 2011. [published].

5. J.-Z. Huang, S. Zhou, J. Huang, C. Berger, P. Willett, ``Progressive Inter-carrier Interference Equalization for OFDM Transmission over Time-varying Underwater Acoustic Channels," IEEE Journal of Selected Topics in Signal Processing, Dec. 2011. [published].

6. J. Huang, L. Liu, W. Zhou, and S. Zhou, "Large-Girth Nonbinary QC-LDPC Codes of Various Lengths," IEEE Trans. on Communications, vol. 58, no. 12, pp. 3436 -- 3447, Dec. 2010. [published].

7. Z. Peng, H. Mo, J. Liu, Z. Wang, H. Zhou, X. Xu, S. Le, Y. Zhu, J.-H. Cui, Z. Shi, S. Zhou, ``NAMS: A Networked Acoustic Modem System for Underwater Applications," Proc. of MTS/IEEE OCEANS Conference, KONA, Hawaii, September 19-22, 2011. [published]

8. W. Zhou, Z.-H. Wang, J. Huang, and S. Zhou, ``Blind CFO Estimation for Zero-Padded OFDM over Underwater Acoustic Channels," Proc. of MTS/IEEE OCEANS Conference, KONA, Hawaii, September 19-22, 2011. [published].

9. Z.-H. Wang, S. Zhou, J. Preisig, K. Pattipati, and P. Willett, ``Per-Cluster-Prediction Based Sparse Channel Estimation for Multicarrier Underwater Acoustic Communications," IEEE International Conference on Signal Processing, Communications and Computing, Xi'an, China, September 14-16, 2011. [published].

10. P. Carroll, S. Zhou, H. Zhou, J.-H. Cui, and P. Willett, ``Localization and Tracking of Underwater Physical Systems," Proc. of CHINACOM, August 17 - 19, 2011. [published].

11. J. Huang, Z.-H. Wang, S. Zhou, and Z. Wang, ``Turbo Equalization for OFDM Modulated Physical Layer Network Coding," The Twelfth IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), June 26-29, 2011. [published].

12. W. Tang, J. Huang, L. Wang, and S. Zhou, "Nonbinary LDPC decoding by min-sum with adaptive message control," Proc. of ICASSP, Prague, Czech Republic, May 22-27, 2011. [published].

13. Z.-H. Wang, S. Zhou, G. B. Giannakis, C. R. Berger, and J. Huang, "Frequency-Domain Oversampling for Zero-Padded OFDM in Underwater Acoustic Communications," in Proc. of Global Communications Conference, Miami, Florida, USA, Dec. 6-10, 2010. [published].

14. J. Z. Huang, S. Zhou, J. Huang, J. Preisig, L. Freitag, and P. Willett, ``Progressive MIMO-OFDM reception over time-varying underwater acoustic channels," in Proc. of 44th Asilomar Conf. Signals, Systems, and Computers, Pacific Grove, CA, Nov. 2010. [published].

PATENTS

S. Zhou, B. Li, P. Willett, M. Stojanovic, and L. Freitag, ``Apparatus, Systems and Methods for Enhanced Multi-Carrier Based Underwater Acoustic Communications", US7,859,944, granted December 28, 2010.

S. Zhou, J.-Z. Huang, and Z.-H. Wang, ``A Progressive Receiver for Multicarrier Transmission in Time-Varying Underwater Acoustic Channels", Invention Disclosure, #11-025.

HONORS/AWARDS/PRIZES

Shengli Zhou has been upgraded as a Senior Member of IEEE, since August 2011.

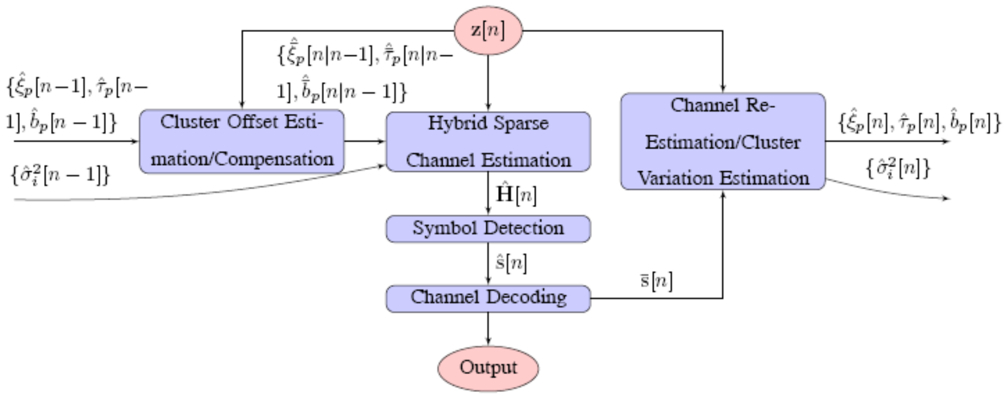


Figure 1. Flow chart of the processing for the nth block in the proposed block-to-block receiver design.

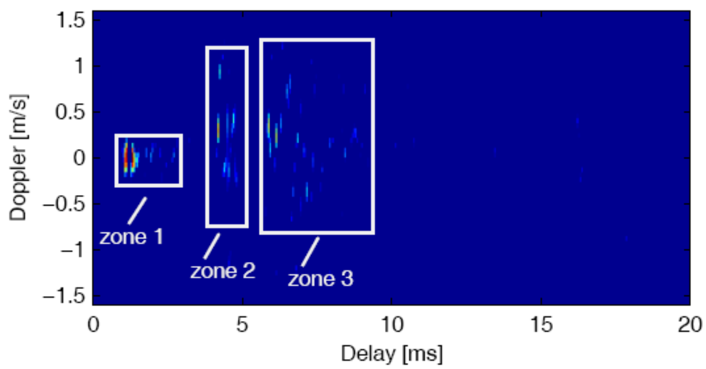


Figure 2: Sample of a channel estimate. Paths in the first zone correspond to direct transmission, while paths in the second and the third zones correspond to the surface/bottom reflections.

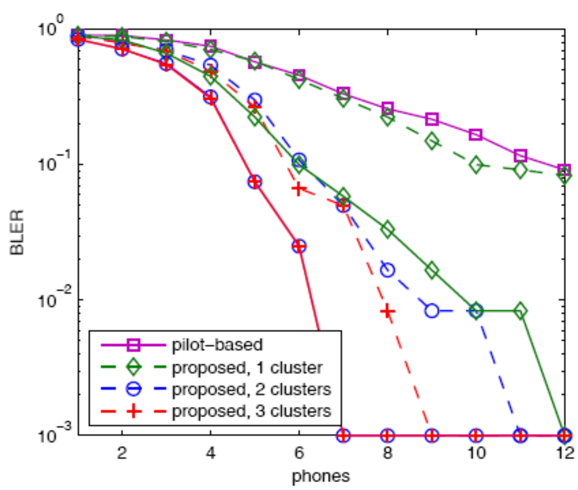


Figure 3: BLER performance of the ICI-aware receiver with different channel estimation schemes, 16-QAM. Dashed lines: proposed method without using the zone information; solid lines: proposed method using the zone information.

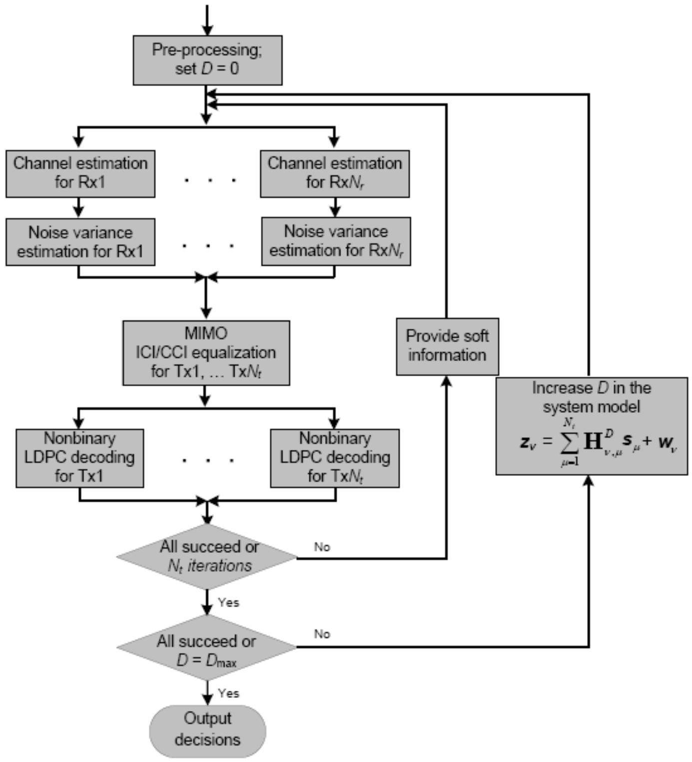


Figure 4: The progressive intercarrier interference and cochannel interference mitigation receiver for MIMO-OFDM.

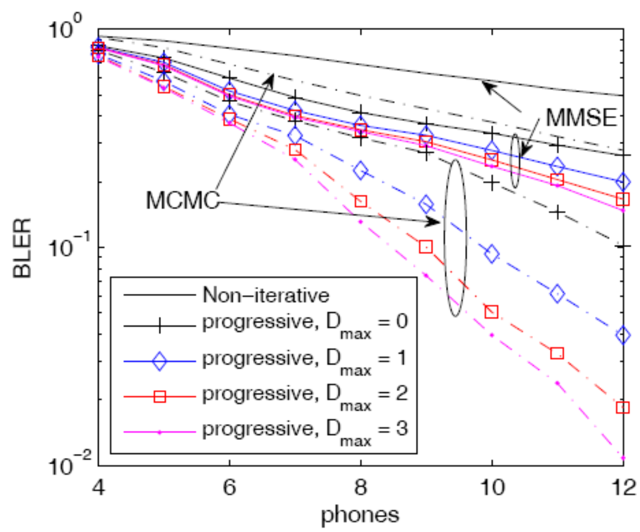


Figure 5: MACE10 experimental results with 4 transmitters, QPSK. Solid lines: Minimum mean-square error (MMSE) equalizer; dash-dotted lines: Markov-Chain Monte-Carlo (MCMC) equalizer.

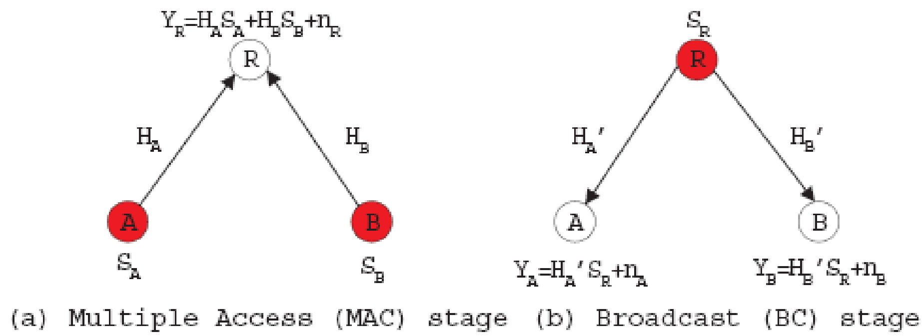


Figure 6: Two terminals A and B exchange information in a block manner with each other via the help of the relay R which can be equipped with multiple receive antennas. The communication consists of a multiple-access (MAC) and a broadcasting (BC) stage.

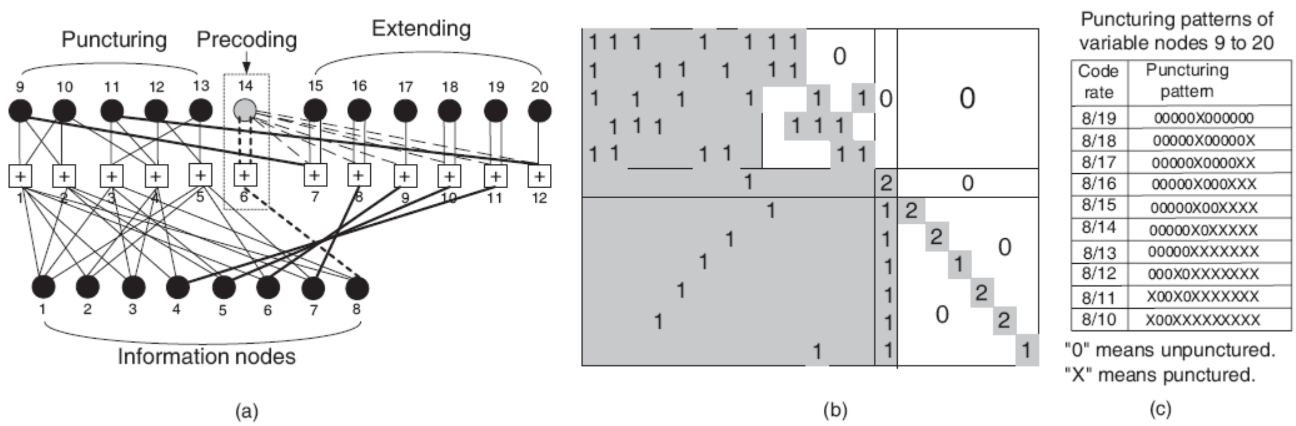


Figure 7: (a). Protograph for nonbinary rate-compatible LDPC codes with rates 8/10, 8/11,. . . ,8/19. (b). The corresponding matrix representation of the designed protograph. (c). Puncturing patterns of variable nodes 9 to 20 for different rates.

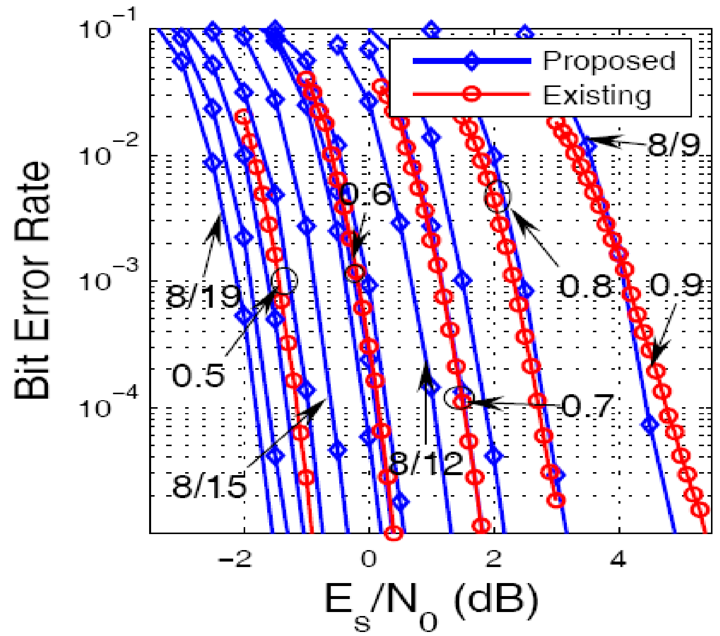


Figure 8: Performance of structured nonbinary rate-compatible low-density parity-check (LDPC) codes.

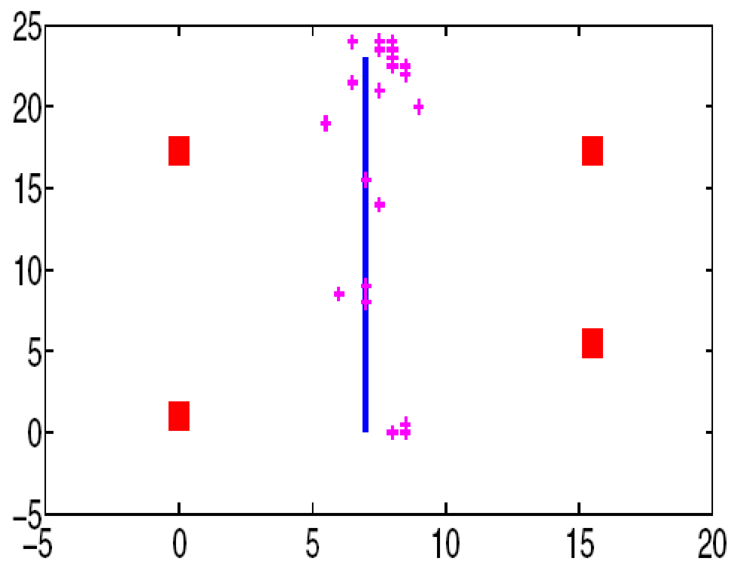


Figure 9: The localization test setup in the swimming pool; scattered are the point estimates

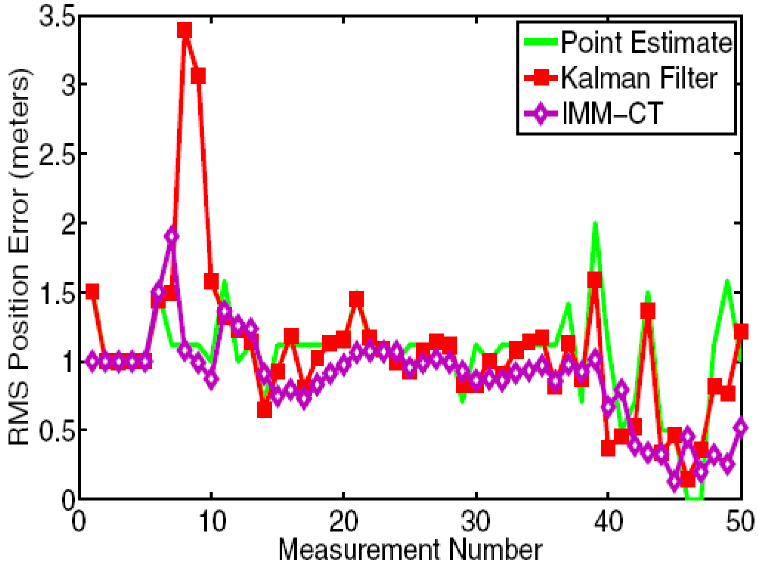


Figure 10: Localization error in the swimming pool. The interacting multi-model (IMM) filter outperforms the Kalman fitler. The localization accuracy is with 1 meter in the swimming pool.

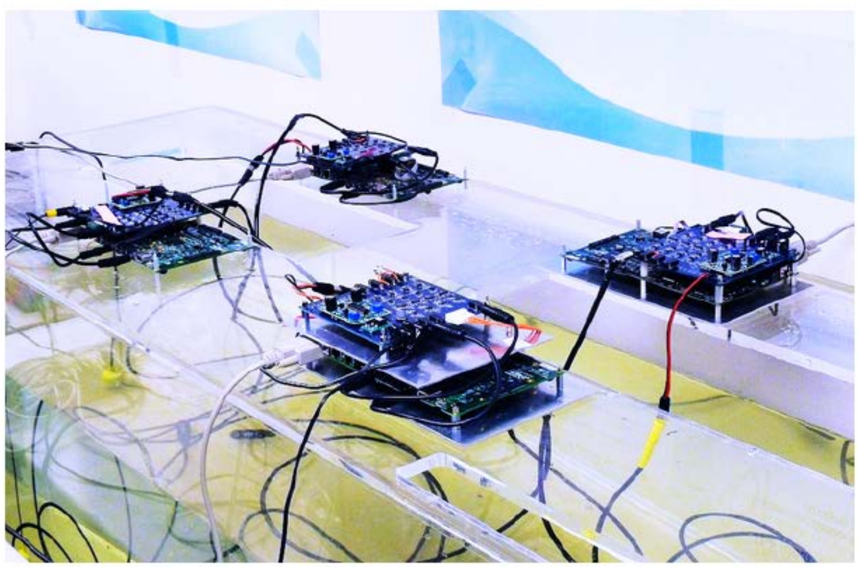


Figure 11: The network testbed with the OFDM acoustic modem prototypes that we deveploped.

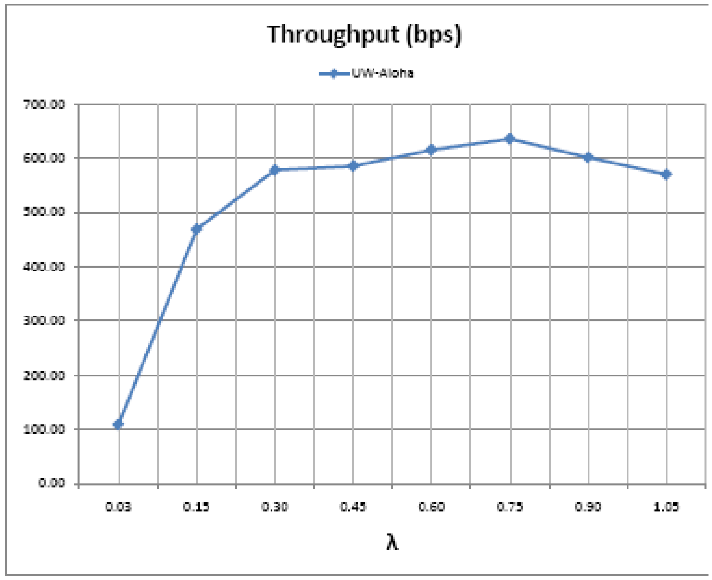
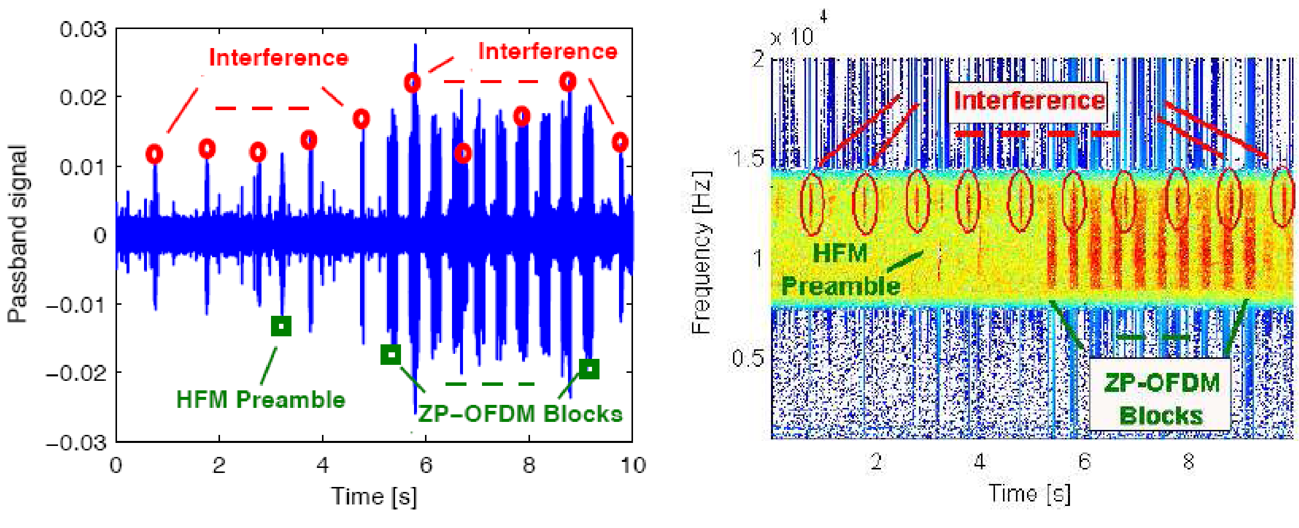


Figure 12: One-hop throughput with UW-Aloha protocol, where three senders try to send messages to one common data sink, using the testbed in Figure 11.



(a) Time domain waveform after bandpass filtering

(b) Time-frequency spectrum

Figure 13: Samples of the time domain waveform and the time-frequency spectrum of the received signal at one hydrophone. The transmitted signal consists of a hyperbolic frequency modulated (HFM) preamble followed by 10 zero-padded (ZP)-OFDM blocks. The circle and the square in the left figure denote the location of interference and the location of useful signal, respectively.

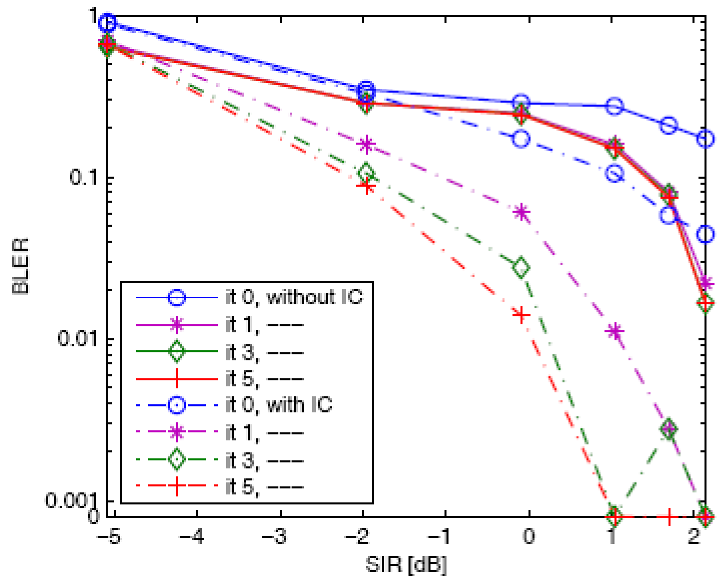


Figure 14: Block error rate of 18 transmissions with and without interference cancellation (IC) versus different signal to interference power ratio